HEAT TRANSMISSION AND DIFFUSION BY FORCED CONVECTION OF A FLUID STREAM

BY

JOHN TERRELL CLAPP, JR.
B.S., Purdue University, 1933
M.S., University of Illinois, 1940

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SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN CHEMISTRY IN THE GRADUATE SCHOOL OF
THE UNIVERSITY OF ILLINOIS, 1942

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INTRODUCTION

The convective transfer processes which take place in a fluid stream include fluid friction or momentum transfer, mass transfer, and heat transfer. The effect of turbulence on all of these processes was investigated in this work but the main emphasis was placed on heat transfer.

Despite the fact that the National Bureau of Standards in cooperation with the National Advisory Committee for Aeronautics has published several methods of measuring isotropic turbulence, no one has made use of these methods in studying heat transmission or diffusion under known conditions of turbulence. Instead, the tendency has been to reduce the turbulence to a minimum and to explain abnormal results by assuming that they were due to "abnormal turbulence" or "entrance effects."

Because the magnitude of these abnormal effects was commonly supposed to be as great as 50 to 100%, it was planned to study the transfer processes under conditions of turbulence such as that obtaining downstream from grid-type turbulence generators and in tube banks and baffle systems.

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HISTORICAL AND THEORETICAL

In 1883 Osborne Reynolds[4] discovered turbulent motion of fluids. Subsequently he developed much of the theory on turbulent flow and proposed an analogy between momentum transfer and heat transfer which led to the relation:

$$\frac{h}{CG} = \frac{f}{2} \qquad (1)$$

where h is the heat transfer coefficient, C is the specific heat, G is the mass velocity, and f if the friction factor.

Other investigators, notably Prandtl[3] and von Karman[6], have modified Reynolds' concepts and have obtained different equations for turbulent flow and for heat transfer analogies. However, Colburn[1] has proposed a convenient empirical analogy which is satisfactory.

$$j_H = \frac{h}{CG}(Pr)^{2/3} = \frac{f}{2} = F_1(Re) \qquad (2)$$

where Pr is the Prandtl number, j_H is a heat transfer factor introduced by Colburn, and $F_1(Re)$ is a function of the Reynolds number.

The heat transfer data was correlated by equation (2), or by equation (3) which is an equivalent relation used by McAdams[2] in correlating data from a number of sources.

$$Nu = F_2\ (Re) \qquad (3)$$

where Nu is the Nusselt number.

EXPERIMENTAL

The apparatus used in this research consisted of a steam-heated experimental cylinder, a turbulence measuring instrument, turbulence generators of various designs, and an induced draft air duct.

The heat transferred from the experimental surface was measured by the amount of steam condensed in the cylinder, and the temperatures of the experimental cylinder and of the air were measured by means of copper-constantan thermocouples.

The turbulence measuring instrument utilized the principle of thermal diffusion, as advanced by Schubauer[5]. Using

an instrument of this type, Schubauer found that percent turbulence was proportional to the angular width of the wake behind a line source of heat.

The turbulence generators were grids which had interfering elements of various numbers, sizes, shapes, and orientations. The percent turbulence was controlled by the type of grid used and the distance that the grid was placed from the experimental section of the duct.

The air velocity was measured by means of an orifice meter with five replaceable orifices which permitted maximum accuracy at all rates of flow.

Complete hydraulic gradients were measured with a Wahlen micromanometer[7].

RESULTS AND DISCUSSION

Heat transfer results for a single, 1¼-inch diameter cylinder placed normal to the air stream are shown in Table I.

TABLE I

Run No.	Turbulence Generators	Nusselt Number	Reynolds Number	Percent Turbulence
132	NONE	25.3	1669	2.3
135		36.9	3290	1.9
137		53.4	6610	1.5
140		74.5	12310	1.5
142		76.2	12190	
143		97.1	19100	1.3
133	G9	25.3	1669	10.9
134		37.1	3290	10.3
138		60.7	6600	15.7
141		87.1	12210	7.6
144		115.4	18950	8.6

This table shows that there is no effect of turbulence upon heat transfer at low Reynolds numbers and only a moderate effect, 18%, at high Reynolds numbers. These results were interpreted to mean that the laminar film resistance at low Reynolds numbers is substantially the whole resistance to heat transfer, whereas at high Reynolds numbers the resistance of the turbulent core is an appreciable part of the total

resistance. Furthermore this indicates that the thickness of the actual laminar layer is independent of turbulence and that the only effect of turbulence on the "effective" film thickness is a decrease in resistance of the turbulent part of the boundary layer.

A general correlation containing the effects of both the Reynolds number and the turbulence, d, was obtained

$$Nu = c\left(\frac{Re}{Re_o}\right)\left(\frac{Re}{Re_o}\right)^{-\frac{n}{d}} \qquad (4)$$

where Re_o is the value of the Reynolds number where the effects of turbulence disappear, m is the slope of the line for high turbulence, and n is a constant.

A study of tube banks and baffle systems was made, and the results were correlated by equation (3). The linear dimension used in Nu and Re was the outside diameter of the tube, and the velocity was taken as the maximum velocity through the minimum free area.

The effect of turbulence on the diffusion of water vapor from a single cylinder normal to an air stream was comparable to the results for heat transfer from the same shape.

SUMMARY

(1) The effects of turbulence upon heat transmission at different velocities were studied and a general equation expressing these effects was developed.

(2) The relative importance of fluid turbulence and velocity in tube banks and baffle systems was studied.

(3) The analogy between mass transfer and heat transfer was investigated together with the effect of turbulence.

BIBLIOGRAPHY

1 Colburn, A. P., Trans. Am. Inst. Chem. Engrs., **29**, 174 (1933).

2 McAdams, W. H., "Heat Transmission", p. 219, 1st ed., McGraw-Hill Co., New York (1933).

3 Prandtl, L., Physik. Z., **11**, 1072 (1910).

4 Reynolds, O., Phil. Trans. Roy. Soc. (London), **174**, 935 (1883).

5 Schubauer, G. B., Tech. Rept. No. 524 Nat. Adv. Comm. Aero (1935).

6 von Karman, T. H., Trans. Soc. Mech. Engrs. **61**, 705 (1939).

7 Wahlen, Univ. of Ill. Eng. Expt. Sta. Bull., **120** (1921).

VITA

The author was born in Beech Grove, Indiana on September 29, 1912. He attended the public schools of Beech Grove until graduation from high school in 1929. During the next four years he was enrolled as a metallurgical major in the Chemical engineering School of Purdue University from which he received the degree of Bachelor of Science in June 1933. For the next five years he was employed by P. R. Mallory & Co., Inc., Indianapolis, Indiana as an Industrial Chemist, but in September 1938 he left their employ to enroll as a chemical engineering major in the Graduate School of the University of Illinois from which he received the degree of Master of Science in October 1940. He served as a Graduate Assistant in the Inorganic Chemistry Department of the University of Illinois for three years and in the Chemical Engineering Department of that University during the Summer Session of 1942.

The author is a member of Triangle Fraternity, Pi Mu Epsilon, Phi Lambda Upsilon, Omega Chi Epsilon, and Sigma Xi.